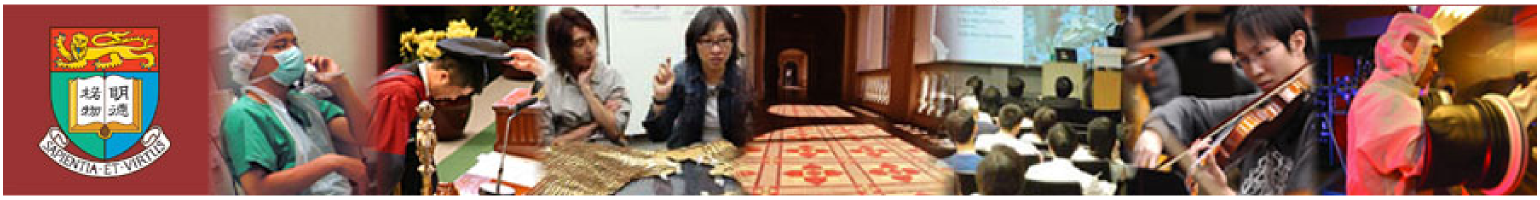

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Power Control in Multihop Cellular Networks with Multiple Radio Access Technologies

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***Abstract*—Multihop communication has attracted a lot of attention as an effective transmission strategy for future cellular networks. It can be an effective technique to increase data rate and enhance coverage. However, multihop relaying with a single Radio Access Technology (RAT) may not be able to provide the flexibility required for wireless cellular network which has moved towards heterogeneity. Therefore, multihop cellular network needs to be integrated with multi-RAT to provide the required flexibility in the cellular architecture . When multihop cellular network is provided with multi-RAT capability, RAT selection for a certain transmission session becomes part of its resource management. RAT selection decision depends on the characteristics of the radio links and the availability of resources in the different RATs. A careful control of power between user and relay is required to exploit multi-RAT and multihop capabilities to their maximum potential. In this paper, we formulated a RAT selection and a transmission power control for a mobile user and relay using an indifference curve. We selected the RAT and allocated the power for a single users transmission such that the interference created by the mobile user and the relay is minimized and the achievable data rate is satisfied.**

***Index Terms*—Power Control, Multihop network, Multi-RAT**

I. Introduction

A conventional cellular network is limited in its capacity and coverage. Due to the unpredictable nature of a wireless channel, transmission of high data rate application (video streaming, gaming) is challenging. Two basic approaches can be adopted in a conventional cellular network to increase its quality of service: either decrease the distance between the user and the base station or increase the power of transmission. Distance can be decreased by employing more base stations, but this is not cost effective, and increasing the transmission power causes interference in the network. Therefore, both options are not feasible. Alternatively, another technique, which can increase the quality of service of a network without increasing the transmission power and is relatively inexpensive is multihop relaying. The concept of multihop relaying employed in a conventional cellular network is called multihop cellular network (MCN). MCN promises to provide high data rate without tremendously increasing the cost or the interference in the network. This method has been extensively studied and proved to provide better capacity and cell coverage than conventional cellular network. Relaying in cellular network can provide the same quality of service to a user at a larger distance from the base station as it provides to a user closer to the base station. Over the years, because of its capacity and coverage benefits, MCN has gained popularity.

Presently, MCN is working with a single Radio Access Technology (RAT). A RAT is a physical layer connection method for a radio-based communication network. Many different RATs have been developed or are being developed. If an MCN is provided with the capability of more than one RAT, then more flexibility is available in the network. A device with more than one RAT working is said to have Multi-RAT (MRAT) capability.

Several existing algorithms have proposed a centralized resource allocation for multihop cellular network. In [1], the authors proposed centralized algorithm for resource scheduling with a small number of fixed relays in the network with a throughput-optimal scheduling policy. In [2], the authors proposed an algorithm called Integrated Radio Resource Allocation (IRRA). They considered route selection as an extra dimension of resource management in MCN. Another work on joint relay selection and resource allocation was done in [3]. A resource allocation jointly with routing is proposed in [4]. A centralized and a distributed algorithm are proposed in [5] for multi-user wireless relaying. Power is allocated to maximize the minimum rate of all users or weighted sum of rates. Fixed relays are present in the network and already assigned to the users. In [6], the authors proposed a cross layer relay selection for a single cell scenario. All the work is aimed at either power minimization or throughput maximization of each of the paths of the MCN. The effect of interference is not considered. In contrast, [7] proposed an interference-aware joint optimization of power control, scheduling and relaying.

For RAT selection, recently some work has been done for heterogeneous wireless networks. In [8], a user terminal allocation to RAT has been studied with demand and capacity constraints. The objective is to minimize the transmit power in multiuser OFDM system. The RATs considered are IEEE 802.11 WLAN and 3GPP LTE, an unlicensed and a licensed technology. In [9], the authors discussed resource allocation with the assumption that the user is configured to select the best RAT strategy. The RAT allocation algorithms studied are based on rate maximization or load-aware rate maximization. The existing RAT selection algorithms based on rate maximization are not effective in a multihop scenario. RAT selection cannot be done separately, it has to be done in conjunction with resource (transmit power to user and relay) allocation. If you perform RAT selection based on rate maximization, maximum power will be allocated to the user and relay. Whereas in a multihop cellular network, transmission power needs to be carefully allocated between the user and the relay, to reap the full benefits of using multihop in the network.

In this paper, we study the power control in MCN with multiple RATs. We studied the problem of RAT selection and transmission power control between a mobile user and the relays for a RAT such that the interference created in the network is minimized and required data rate of the user is satisfied. We formed an indifference curve between user's and relay's transmission power for an achievable data rate of a single user for any RAT capability. The indifference curve helps us to form a balance between the user's and the relays' transmission power such that the network is benefitted for the allocation. Different RAT will have different power allocation for an achievable data rate that minimizes interference. In addition the minimized interference values for each RAT is also different. Out of these, we select the RAT for a particular transmission of a user that will create minimum interference.

The rest of the paper is structured as follows. Section 2 discusses the background and motivation, Section 3 describes the system model, Section 4 illustrates the problem formulation and the algorithm for RAT selection and power allocation. Section 5 shows the performance evaluation and Section 5 concludes the paper.

II. Background and Motivation

In this section, we will discuss background knowledge required and provide motivation to integrate MCN with MRAT.

MCN employs multiple hops in transmission of data from/to the base station using relays in a macrocell. The benefits an MCN can provide are the enhancement of coverage, reduction in the transmit power and an increase in system capacity. MCN can provide coverage to the users in dead spot areas (e.g., macrocell edges, indoors). With multiple hops a connection can be established between these dead spot users and the base station. As the transmission is segmented into multiple hops, the transmission power required for direct transmission is more than the total transmit power through multiple hops. In MCN, as the transmit power of each hop is smaller, the interference range is reduced as compared to the interference range of direct transmission, thus increasing frequency reuse and the system capacity.

RAT is a physical layer connection technique for a radio-based communication network. Examples of a RAT are LTE, WIMAX and WLAN. If more than one RAT is available at the physical layer of a device, the device is said to have MRAT functionality. Each RAT is planned and deployed independently. Some of the characteristics that distinguish among different RATs are radio coverage, spectral density, cell capacity and peak data rate. For cellular networks, different RATs have been developed. Future cellular network is expected to be heterogenous and multiple RATs will exist on same device, providing users the flexibility to choose the RAT satisfying their preferences. The gains that can be achieved from managing an MRAT depends on the cell layout of different RATs and the user distribution in the area. The two extreme cases of a cell layout are, a) co-located layout in which common base stations are to be used for different RATs and b) non-co-located layout in which the base stations of two RATs are at a maximum distance from each other.

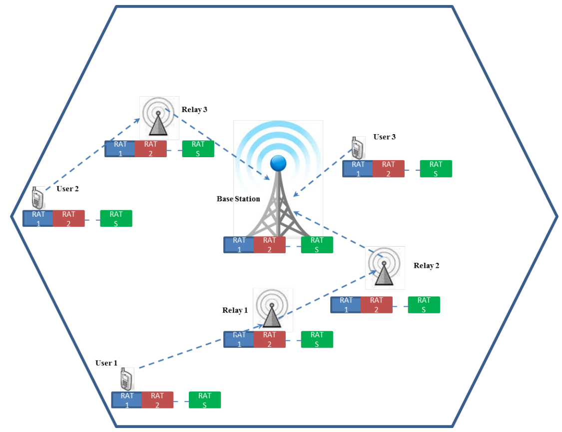


Fig. 1. MRAT-MCN in a macrocell.

By integrating the functionality of MRAT with MCN, a heterogeneous system is formed with different access technologies and multi-hopped transmissions. We call this MRAT-MCN. Figure 1 shows a scenario of a colocated layout of an MRAT in MCN. A total of S RATs are available to the base station, relays and users. User 1 connects to the base station in three hops through Relay 1 and Relay 2 using any of the RATs depending on the traffic requirement, whereas User 2 connects in two hops and User 3 is directly communicating with the base station.

With the flexibility of RAT and quality-of-service benefits of MCN in MRAT-MCN, resource management issues become challenging. As the conventional cellular network moves towards multihop, relay selection becomes an added dimension to the resource management problem in addition to the subcarrier, time and power allocation. Further, with the availability of various radio access technologies in MRAT-MCN, a new dimension of RAT selection also becomes part of resource management.

III. System Model

In this section, we will discuss the system model for the RAT selection and power control framework. We consider a base station o with N number of users and a total of R relays deployed on fixed locations in the macro cell. The N users and R relays support a total of S RATs in the network. We used i, j and s to represent any particular user, relay and RAT in the network. Here, we assume a co-located cell layout for the RATs, i.e. they all share the same base station and cell structure. The cellular operator will act as a multi access mobile network operator. All the RATs support cooperative communication.

The cooperative transmission involves two phases. In the first phase, direct transmission takes place. Let $\Gamma_{i,o}^{s}$ be the signal-to-noise ratio of the direct transmission from a user i to base station o using the sth RAT. In the second phase, the signal-to-noise is considered at the base station resulting from the relay j providing relaying for mobile user i using the sth RAT for both. We denote this signal-to-noise ratio as $\Gamma^s_{i,j,o}$. We employed maximal ratio combining [10] at the receiver and used amplify-and-forward [11] cooperation protocol as our relaying mechanism. If a relay j is part of the two-hop cooperative communication, then the achievable data rate of a user i using the sth RAT is defined as

$$\begin{aligned} R^s_{i,j,o} &= \gamma W \log_2 \left(1 + \Gamma^s_{i,o} + \sum_{j \in Q} \Gamma^s_{i,j,o} \right), \\ &= \gamma W \log_2 \left(1 + \frac{P_i G^s_{i,o}}{\sigma^2} \right. \\ &\quad \left. + \frac{P_j P_i G^s_{j,o} G^s_{i,j}}{\sigma^2 \left(P_j G^s_{j,o} + P_i G^s_{i,j} + \sigma^2 \right)} \right), \end{aligned} \tag{1}$$

where

- γ is the bandwidth factor;
- W is the bandwidth;
- P_i is User i's transmit power;
- P_j is Relay i's transmit power;
- $G^s_{i,o}$ is the channel gain from User i to base station o;
- $G^s_{i,j}$ is the channel gain from User i to Relay j;
- $G^s_{j,o}$ is the channel gain from Relay j to base station o;
- σ is the additive white Gaussian Noise.

The channel gain is different for each RAT, and depends on the path loss factor. We modelled channel gain from a source f to destination g using the sth RAT as

$$G^s_{f,g} = K_0 d_{f,g}^{-^s} 10^{X_{f,g}/10}, \tag{2}$$

where K_0 is a channel gain factor, $d_{f,g}$ is the distance between between f and g, l^s is the path loss of the sth RAT and $X_{f,g}$ is a Gaussian random variable with zero mean and σ^2 variance.

IV. Power Control and RAT Selection

In this section, we will formulate the problem of RAT selection and power control between user and relay. Then, we use the indifference curve to select the RAT and transmit power for user and relay in the multihop cellular network.

A. Problem Formulation

We formulate the problem from the network operators point of view. A user can achieve better data rate through cooperation in a multihop network. A relay gets incentives for cooperation and for the operator, coverage and capacity are enhanced. The enhanced coverage and capacity will allow the operator to cater to more users in the cell without increasing the bandwidth. However, careful allocation of transmission power between the mobile user and the relay is required to take advantage of the multihop technique. It is a network centric approach and the exact number of hops including the relays are decided by the operator. In addition the exact path in which the transmission will take place is decided before the power control. We formulate the power allocation between User i and Relays j both using the s^{th} RAT for transmission of user i data to the base station as

TABLE I
Analogy in economics and Multihop Cellular Network

Economics	MCN
Economic agent	Mobile network(operator)
Good 1	Transmission power of mobile user
Good 2	Transmission power of mobile relay
Output product	Achievable data rate
Cost	Interference created

$$\begin{aligned} \arg\min_{s \in S} \ (\underset{P_i, P_j}{\text{minimize}} \quad & I^s_i(P_i, P_j)) \\ \text{subject to} \quad & R^s_{i,j,o}(P_i, P_j) = r, \\ & P_i > 0, P_j > 0. \end{aligned} \tag{3}$$

Here j can represent one or more than one relays involved in the transmission and $I^s_j(P_i, P_j)$ is the interference created in the network by User i when it is transmitting its data using the cooperation of Relay j and r is the achievable data rate. It is defined as

$$I^s_i(P_i, P_j) = \sum_{k \in N^c_i} P_i G^s_{i,k} + \sum_{l \in N^c_j} P_j G^s_{j,l}, \tag{4}$$

where N^c_i and N^c_j are the set of users present in the interference range of User i and Relay j, respectively. The knowledge of N^c_i and N^c_j can be computed by sending a broadcast message in the cellular network periodically [12]. Both user and relay are using the s^{th} RAT. Our objective is to choose an RAT s and allocate power to the i^{th} user and the j^{th} relay such that the interference created using the s^{th} RAT is minimized and the achievable data rate is satisfied. The operator can select more than one relay for cooperation in transmitting user i's data. If more than one relay is selected, the transmission power allocated for the relay can be further split between different relays. As it is a network-centric approach, information of position of users of different RATs, path loss model and users being affected by a transmission are known. The interference created by a user in the network can then be computed for different power allocations.

B. Transmission Power Allocation and RAT selection Algorithm using Indifference Curve

In this section, we will discuss the transmission power allocation and RAT selection algorithm for a mobile user to transmit at any particular time instant. Our RAT selection algorithm aims at minimizing the interference created by the user. The user and relays that are part of transmission will use the same type of RAT for a particular communication. As already discussed transmission power allocation is important in cooperative multihop communication. We will also discuss the power balancing between mobile user and a mobile relay. Power balancing is critical in improving the performance of a multihop cellular network. If the transmission power allocated to user is more, then that allocated to mobile relay is less and as the transmission power to mobile user decreases, the transmission power of relay increases.

Our RAT selection algorithm works as follows. A user wants to transmit data to the base station. As already mentioned we are using a co-located cell layout, and all the RATs share the same base station. The user sends a service request to the MRAT network operator. The network operator will first decide on the relays to be used for this particular transmission. The MRAT-MCN network operator will then compute a set of equally preferable transmission power allocation for each RAT.

For each RAT, we computed a feasible set of transmission power and represented it as an indifference curve. To compute the indifference curve, we formed an analogy between the economic scenario and the multihop cellular network as shown in Table I. The basic assumption of consumer behavior is that an economic agent will always behave rationally. If provided with two options, an economic agent will choose the option that maximizes its utility. However, if the two options provide the same utility then the consumer will be indifferent to the two options. This phenomenon can be explained by an indifference curve. In microeconomics theory, an indifference curve is used in situations where an individual has to choose two or more of different goods but has no preference for selecting one option over another. An indifference curve will be a line that joins all the points representing different combination of goods that provide the same level of satisfaction to an economic agent. In this the different combinations of the good has to produce the same output. If the individual is producing the same output with different combinations of the good, then he can choose to use the combination of good with minimum cost involved. The feasibility condition in the economic scenario is that the output product should be same. In our scenario, the feasibility conditions are the two conditions defined as constraints in the formulation of equation 3. The condition are:

- The achievable data rate of a user should be satisfied and;
- The transmission power allocated to user and relay should be greater than zero.

Satisfying the above condition the feasible power sets are formed using equation 1. An expression for transmission power of relay is

$$P_j = \frac{B\left(\sigma^2\left(P_i G_{i,j} + \sigma^2\right)\right)}{P_i G_{j,o} G_{i,j} - B G_{j,o} \sigma^2}, \tag{5}$$

where $B = 2^{\frac{R_{i,j,o}}{W \times \gamma} - 1 - \frac{P_i G_{i,o}}{\sigma^2}}$.

The indifference curves are continuous, therefore all the point on the curve are part of the feasible set. After the computation of the feasible set, the point that provides the lowest interference will be the power allocation selected for that particular RAT. The power allocation is selected for each RAT and how much interference that particular power allocation will create in their network.

Now with the minimum interference value for each RAT, the RAT is selected by the MRAT-MCN as follows

$$\text{RAT } s \text{ is selected} = \arg\min_{s \in S} I_i^s. \tag{6}$$

TABLE II
SYSTEM PARAMETERS TO OBTAIN THE NUMERICAL RESULTS

Parameters	Value
Bandwidth factor γ	0.5
Path Loss exponent	5
Distance between user and base station	$1km$
Distance between user and relay	$0.5km$
Angle between user-base station to user-relay	60^o
Bandwidth W	1000
Noise σ	10^{-10}

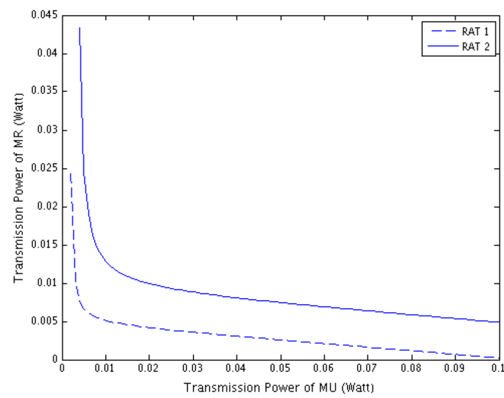


Fig. 2. Feasible power allocations for RAT 1 and RAT 2 for an achievable data rate of 10 kbps.

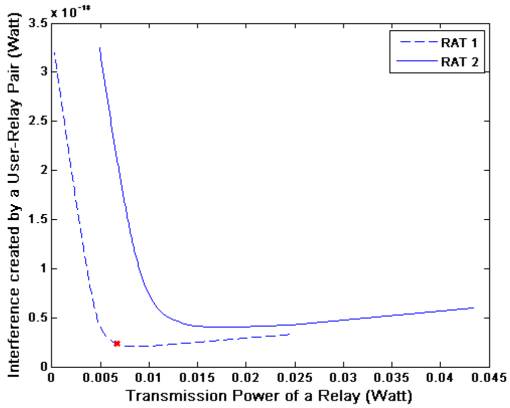
The transmission power that provides that interference is the transmission power allocated to user and relay for that particular transmission. The MRAT-MCN operator will allocate the transmission power to the user and the relay and inform them the RAT they have to use for transmission.

Our criteria to choose a RAT for transmission for a user i is the one which creates less interference in the network. This way we will be able to exploit the full benefits of MRAT-MCN.

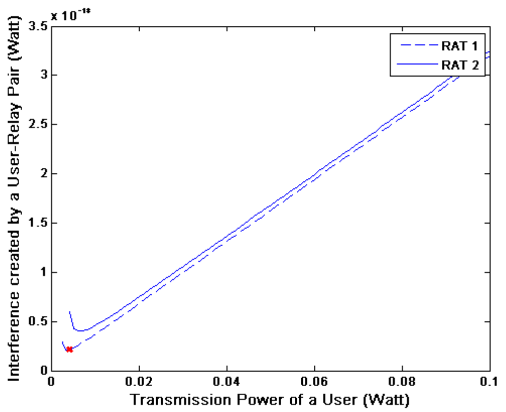
V. NUMERICAL SIMULATIONS

In this section, we will show the performance of the RAT selection and power allocation algorithm. We considered the RAT selection and power allocation for a single user and a relay who are communicating with the base station. Both the user and relay supports two RATs. We are using a co-located cell layout, and all the RATs share the same base station. But still the channel condition of each RAT is different. The common parameters for both the RATs are shown in Table II.

Figure 2 shows a feasible power allocation set for a datarate of 10 kbps. The feasible power allocation for both RAT 1 and RAT 2 are shown on the same plot. We study how user transmission power and relay transmission power are related for any RAT. For RAT 1 and RAT 2, we can observe that as the user's transmission power increases, the relays transmission power will decreases and it is true vice versa as well. This relationship is obvious because if a user is using more transmission power, then the relay chosen is closer to



(a) Relationship between relay's transmission power and interference created a user-relay pair.



(b) Relationship between user's transmission power and interference created a user-relay pair.

Fig. 3. Interference created by a user-relay Pair

the base station and the transmission power it needs to use is less.

The RAT selection is based on the interference value. A random number of interfering members are considered for each simulation. Figure 3 shows the effect of user's and relay's transmission power on the interference created by the user-relay pair in the network. Figure 3(a) shows the decrease in interference created by a user-relay pair in the network as the transmission power of the relay from the feasible set increases. Similarly, Figure 3(b) shows the increase in the interference created by a user-relay pair in the network as the transmission power of the user from the feasible set increases. The minimum interference created by RAT 1 is $2.0619e-019$ and by RAT 2 is $4.0004e-019$ as shown in Figure 3(a) and 3(b). RAT 1 has a minimum value as shown by a red dot in Figure 3, therefore it is selected. The transmission power of user and relay at which this interference occurs will be the optimal power for this transmission session.

Thus, we can conclude that transmission power of relay and user are dependent on each other and each pair will create an interference in the network and the feasible pair of a RAT that creates the least interference in the network should be selected for transmission with the RAT.

VI. Results and Future Research Directions

We proposed a transmission power allocation and RAT selection algorithm framework. As the cellular network is interference limited, we considered the allocation as an interference minimization problem. This work can be extended, to consider load balancing between different relays and different RATS for fairness in cellular network. The relays as well as RATs should not be overloaded. Admission control will be an interesting direction to look into for an MRAT-MCN. As relays can be mobile so mobility management should also be discussed as part of resource management in MRAT-MCN. For MRAT-MCN, all the work discussed has considered a co-located cell layout for MRATs. Non-colocated MRAT-MCN would be another interesting direction for research. Another dimension which needs to be studied for MRAT-MCN is the handoff of the user between different relays as well as switching between different RATs. Existing handoff and switching parameters needs to be reinvestigated considering the topology characteristics of MRAT-MCN.

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